MULTI-CARRIER OFDM UWB COMMUNICATIONS SYSTEMS

The present invention relates to wideband RF communications systems, and more particularly to ultra-wideband (UWB) communications systems.

Ultra-Wideband Signals have been legal in the United States since February 2002 under conditions stipulated by the FCC Report and Order 02-48. Briefly, UWB signals must never be transmitted with a power spectral density of more than –41.2dBm/MHz in a band from 3.1GHz to 10.7GHz. Elsewhere, the power must be reduced even further to protect existing services. Since the power limit is specified as a power spectral density, the transmit power is proportional to the bandwidth, and hence the desire is to occupy as much bandwidth as possible within economic and feasibility constraints and thereby maximize the possible link range. However, due to the increasing RF path loss with carrier frequency, as well as increasing noise figure of semiconductor devices, initial interest is concentrated on exploiting the spectrum from 3.1 – 4.9GHz.

Two competing standards proposals for UWB have emerged, one identified with Motorola and the other identified with a coalition of companies referred to as the Multiband OFDM Alliance (MBOA). The MBOA-OFDM (hereinafter "MB-OFDM") system borrows heavily from the existing wireless LAN concepts for 802.11a and 802.11g. The OFDM signal consists of 128 sub-carriers. These carriers occupy a 528MHz, so the sub-carrier spacing is 4.125MHz. Since the carrier spacing is 4.125MHz, it follows that the OFDM symbol length must be 1/4.125e6 = 242.42 ns. To allow for inter-symbol interference a zero-energy prefix of ¼ of the symbol length (60.6 ns) is applied in place of the more traditional cyclic prefix. Finally a guard period of 5 samples (9.47ns) is added. The total OFDM symbol length is 312.5ns.

Of the 128 sub-carriers, 5 are set to nulls at the band edges, so that the actual occupied bandwidth is only 507.375MHz (marginally wider than the mandated 500MHz). Moreover, only 100 of the 128 sub-carriers are information-bearing; the others are either pilots, user-defined, or nulls. The 100 information-bearing tones carry QPSK modulation, thus providing 2 bits each, or 200 bits per OFDM symbol. The total gross information rate is thus (200/312.5e-9), or 640Mbps. After channel coding redundancy is taken into account, the maximum protected data rate is 480Mbps (3/4 rate code).

As noted above the plain use of OFDM results in an occupied spectrum of just over 500MHz, which is less than a third of the UWB spectrum available below 5GHz. Since the transmitted power is proportional to the occupied bandwidth, failure to address this would

have a serious impact on the available range. The MB-OFDM specification uses a 3-band hopping scheme to realize a 3-fold increase in bandwidth. The method adopted is that successive OFDM symbols are transmitted in different bands according to a predefined hopping sequence of length 6. These hopping sequences are designed to minimize collisions between uncoordinated piconets and are called Time- Frequency Interleaving (TFI) Codes. Example sequences include {1,2,3,1,2,3}, {3,2,1,3,2,1}, {1,1,2,2,3,3} etc., where each index represents a specific 528MHz frequency band.

The following table shows how PHY-SAP data rates from 53.3 to 480Mbps are derived from the basic 640Mbps uncoded bit rate.

Data Rate (Mb/s)	Modulation	Coding rate (R)	Conjugate Symmetric Input to IFFT	Time Spreading Factor (TSF)	Overall Spreading Gain	Coded bits per OFDM symbol (N_{CBPS})
53.3	QPSK	1/3	Yes	2	4	100
55	QPSK	11/32	Yes	2	4	100
80	QPSK	½	Yes	2	4	100
106.7	QPSK	1/3	No	2	2	200
110	QPSK	11/32	No	2	2	200
160	QPSK	½	No	2	2	200
200	QPSK	5/8	No	2	2	200
320	QPSK	½	No	1 (No spreading)	1	200
400	QPSK	5/8	No	1 (No spreading)	1	200
480	QPSK	¾	No	1 (No spreading)	1	200

The three mechanisms for introducing redundancy are as follows:

1. Convolutional Coding with rates 1/3,11/32,1/2, 5/8 and ¾.
2. Conjugate Symmetric Input to the IFFT, which introduces a factor of ½.
3. Time spreading, where complete OFDM symbols may be repeated on different frequencies.

All three of these techniques are briefly described in the following paragraphs.

Convolutional Coding - A 64-state convolutional encoder is used with 3 polynomials to create a 1/3-rate mother code. Puncturing of the output is used to adapt the code rate by reducing the redundancy. Different puncturing patterns are employed to obtained the specified rates according to the MB-OFDM specification. At the receiver, depuncturing is performed by inserting zeros in place of the punctured out bits, before processing by the Viterbi decoder.

Conjugate Symmetric Input to the IFFT - The sum of two complex exponential equal and opposite angular frequencies and complex conjugate coefficients can be shown as follows.

$$
\begin{aligned}
&\tfrac{1}{2}\left[(a+bj)\exp(j\omega t)+(a-bj)\exp(-j\omega t)\right]\\
&=\tfrac{1}{2}\left[(a+bj)(\cos(\omega t)+j\sin(\omega t))+(a-bj)(\cos(\omega t)-j\sin(\omega t))\right]\\
&=\tfrac{1}{2}\left[a\cos(\omega t)-b\sin(\omega t)+j(b\cos(\omega t)+a\sin(\omega t))+a\cos(\omega t)-b\sin(\omega t)-j(b\cos(\omega t)+a\sin(\omega t))\right]\\
&=a\cos(\omega t)-b\sin(\omega t)\\
&=\sqrt{a^2+b^2}\cos(\omega t+\phi);\phi=\arctan(b,a)
\end{aligned}
$$

The corresponding time sequence (the result of the IFFT) is thereby forced to be real, since it represents an integer number of cycles of a cosine wave of amplitude and phase defined by $|a+bj|$ and $\text{angle}(a+jb)$ respectively, as demonstrated by mathematical identities above.

The use of this principal in the MB-OFDM transmitter is as follows. There are allocated100 complex QPSK symbols in the 128pt IFFT. Initially, only 50 of these are filled with QPSK symbols corresponding to positive frequencies, the remaining 50 are copied to the negative frequency bins but with a complex conjugate operation. The FFT bins corresponding to d.c. and $\pm f_s/2$ are set to zero along with the four other null tones. Since the result of the IFFT is guaranteed to be entirely real, hardware simplifications can be realized in the transmitter (only the real arm of the quadrature upconversion need be realized, and certain arithmetic operations in the IFFT can be eliminated).

Time Spreading - For data rates of 53.3, 55, 80, 106.7, 110, 160 and 200 Mbps a time-domain spreading operation is performed with a spreading factor of two. The time-domain spreading operation consists of transmitting the same information over two OFDM symbols. These two OFDM symbols are transmitted over different sub-bands to obtain frequency diversity. For example, if the device uses a time-frequency code [1 2 3 1 2 3], the information in the first OFDM symbol is repeated on sub-bands 1 and 2, the information in the second OFDM symbol is repeated on sub-bands 3 and 1, and the information in the third OFDM symbol is repeated on sub-bands 2 and 3.

A block diagram of a known MB-OFDM UWB transmitter is shown in Figure 1. Input data is first scrambled (block 101), then encoded (blocks 103, 105), then formed into data symbols and finally OFDM symbols (blocks 107, 109). The frequency-domain OFDM symbols are then transformed into a baseband time-domain signal (blocks 111, 113) and

upconverted to an RF time-domain signal (blocks 115, 117) applied to an antenna 119. Note in block 107 (IFFT) the insertion of pilot tones and the addition of a cyclical prefix and a guard interval as explained previously. Further note in block 115 the application of a time-frequency code as explained previously.

A block diagram of a known MB-OFDM UWB receiver is shown in Figure 2. The receiver is a quadrature receiver having an RF front end 230 including a I branch 210 and a Q branch 220. In block 240, an FFT is performed to transform the received time-domain signal back into a frequency-domain OFDM symbol; concurrently, synchronization is performed, and the cyclical prefix is removed. Block 251 is responsible for frequency domain equalization, which may be achieved, for example, by dividing each complex frequency-domain signal sample by its corresponding frequency-domain channel estimate. For best results the carrier phase estimate initially obtained from the pre-amble should be periodically updated by tracking algorithms (block 253) as the burst progresses. Blocks 207, 203 and 201 perform the inverse operations of blocks 107, 103 and 101.

In the foregoing MB-OFDM approach, although the average PDS of the signal over the course of a TFI code satisfies FCC requirements, as the time interval over which the average is calculated is shortened, an argument may be made that strict compliance with the requirements is not achieved. A need therefore exists for alternative approaches that achieve strict rules compliance while preserving the advantages of the MB-OFDM approach.

The present invention, generally speaking, provides for signaling methods in which multiple sub-bands of a transmission band are continuously occupied by an OFDM signal that would otherwise occupy only a single sub-band. In accordance with one embodiment, steps include producing an OFDM symbol; transforming the OFDM symbol to produce an OFDM signal; upsampling the OFDM signal to produce an upsampled OFDM signal; applying a pseudo-random code to the upsampled OFDM signal to produce a coded OFDM signal; and upconverting the coded OFDM signal to produce a radio frequency signal. In accordance with another embodiment, steps include producing an OFDM symbol; transforming the OFDM symbol to produce an OFDM signal; and upconverting the coded OFDM signal to produce a radio frequency signal; wherein the radio frequency signal occupies multiple ones of the following sub-bands: a first sub-band from about 3200MHz to about 3700MHz; a second sub-band from about 4000MHz to about 4200MHz; and a third sub-band from about 4200MHz to about 4800MHz. In accordance with still another embodiment, steps include producing a sequence of N consecutive identical OFDM

symbols; transforming the OFDM symbols to produce corresponding OFDM signals; and upconverting the coded OFDM signal to produce a radio frequency signal; wherein the radio frequency signal occupies N sub-bands of a transmission band.

The present invention may be more fully understood from the following description in conjunction with the appended drawing. In the drawing:

Figure 1 is a block diagram of a known MB-OFDM transmitter;

Figure 2 is a block diagram of a known MB-OFDM receiver;

Figure 3 is a block diagram of a modified direct-sequence OFDM transmitter in accordance with one embodiment of the present invention;

Figure 4 is a block diagram of an exemplary receiver architecture using digital correlators according to one embodiment of the present invention;

Figure 5 is a block diagram of an exemplary receiver architecture using analog correlators according to one embodiment of the present invention;

Figure 6 is a block diagram of a modified MB-OFDM transmitter in accordance with another embodiment of the present invention;

Figure 7 is a block diagram of an exemplary receiver architecture according to another embodiment of the present invention;

Figure 8 is a block diagram of an exemplary receiver architecture according to a further embodiment of the present invention;

Figure 9 is a block diagram of an exemplary receiver architecture according to a still further embodiment of the present invention;

Figure 10 is an explanatory diagram illustrating square time-frequency spreading of OFDM symbols;

Figure 11 is a table setting forth examples of modified spreading schemes; and

Figure 12 is a block diagram of a modified receiver for receiving an OFDM signal using square time-frequency spreading.

Because of the FCC rule mandating very low PSD within the spectrum proposed for UWB transmissions, a strategy in order to maximize transmission range is to occupy as much bandwidth as possible in order to maximize total transmission power. A challenge of UWB systems is to occupy a very wide bandwidth without prohibitive hardware complexity. The present invention addresses this need.

Referring now to Figure 3, a block diagram is shown of a modified direct-sequence OFDM transmitter in accordance with one embodiment of the present invention. Blocks

301, 303, 305, 307, 309, 311 and 313 operate in substantially the same manner as corresponding blocks in Figure 1. Unlike the transmitter of Figure 1, however, in the transmitter of Figure 3, the OFDM symbol is up-sampled by a factor of N in block 321. The resulting upsampled signal is then multiplied by a PN sequence by blocks 323 and 325. As a result, a baseband signal produced by block 313 occupies a wider bandwidth. This greater bandwidth occupancy allows the known TFI code of Figure 1 to be eliminated. Instead, a single-frequency local oscillator 350 is used to up-convert the signal to RF. In an exemplary embodiment, a local oscillator having a frequency of about __ may be used. The resulting RF signal then occupies substantially all of the bandwidth from about 3200MHz to about 4800MHz.

In the transmitter of Figure 3, each complex sample at the output of the IFFT is replaced with a code sequence of length N. The magnitude and phase of the transmitted code sequence is determined by the corresponding complex sample from the transmitter. For example, the length 3 hopping sequence of the known MB-OFDM UWB proposal may be replaced by a chip sequence of length 4 or more.

A block diagram of a receiver for receiving the RF signal produced by the transmitter of Figure 3 is shown in Figure 4. The RF front end 430 of the receiver operates in substantially the same manner as the RF front end of Figure 2. Also, blocks 340, 351 and 353, and blocks 307, 303 and 301 operate in substantially in the same manner as corresponding blocks in Figure 2. Unlike the receiver of Figure 2, however, the receiver of Figure 4 includes digital correlators 450I and 450Q in the I and Q paths, respectively. These correlators constructively combine n consecutive samples, correcting appropriately for the polarity of the individual PN chips before summing them. This results both in a bandwidth compression equal to the bandwidth expansion applied in the receiver and in an increased SNR by the factor n. The phase of the PN sequence used for correlation is set to a pre-arranged value at the end of the preamble, so that by counting from this known starting point both transmitter and receiver can be synchronized without the need for a search algorithm in the receiver.

A receiver using analog correlators is shown in Figure 5.

In the system of Figures 4 and 5, a tradeoff may be made between the choice of spreading gain and the length of the OFDM symbol. If the output of the IFFT in the transmitter is sufficiently wideband to qualify as a UWB signal without further spreading (i.e., >500MHz), then an FDMA fall-back mode is obtained simply by freezing the PN

sequence in the transmitter. This type of operation is useful for multiple piconets in very close proximity. FDMA mode may also be used in cases where link distance is not an issue, such as in some cases of wireless USB. In other cases, it may be more advantageous to consider the use of longer OFDM symbols (occupying a lower bandwidth than 500MHz), compensated by the use of longer spreading codes. This type of operation may be attractive especially in the case of low data rate modes. For example, instead of an OFDM symbol length of 312.5ns and a spreading factor of 4, an OFDM symbol length of 625ns and a spreading factor of 8 might be used.

An advantage of the system of Figures 4 and 5 is that the FFT complexity can remain unchanged as compared to the system of Figures 1 and 2, for example. The process of spreading in the transmitter and despreading in the receiver should leave the samples unaltered in the ideal system. The principle disadvantage of this approach is that in multipath channels, multiple correlators may be needed to collect and combine sufficient energy to obtain the desired performance. Indeed, any delay spread beyond the length of one "chip" period will be scrambled by the PN sequence and appear as noise to the subsequent OFDM processing. Therefore in practical systems a set of correlators must be used with complex tap weights applied to their outputs defined by the complex conjugate of the estimated channel tap weights. The same procedure is used in conventional CDMA receivers including those proposed for UWB and is widely known as a RAKE receiver.

Instead of taking measures during baseband processing to occupy a wide bandwidth, measures may be taken during upconversion. One approach is to take advantage of the aliasing behavior of DACs. Referring to Figure 1, block 113 typically includes or is followed by an anti-aliasing filter. Where it is desired to occupy a specified bandwidth, the anti-aliasing filter may be modified to pass alias components within that bandwidth. A more direct approach is to mix the baseband signal with a comb of continuously present carriers. A block diagram of such a transmitter is illustrated in Figure 6. As compared to the transmitter of Figure 1, in which block 115 produces a TFI code, in Figure 6, a multi-tone generator 615 is used. As a result, the identical OFDM symbol is copied to each sub-band having its frequency generated by the multi-tone generator.

A variety of receiver options may be used to receive the signal produced by the transmitter of Figure 6, allowing for solutions of different complexity and cost. Referring to Figure 7, one option is to receive only one sub-band, for example selecting a sub-band that gives the best preamble reception. The approach may be described as selection diversity. As

compared to the receiver of Figure 2, in the receiver of Figure 7, no predefined frequency hopping occurs. The complexity of the FFT remains the same. Furthermore, narrow-band interference in one of the sub-bands can be avoided in this manner.

Referring to Figure 8, another option is to combine together (non-coherently) the duplicate OFDM symbols from different sub-bands within the analog front end, effectively folding the different sub-bands into a single sub-band. This can be done by allowing different images to fold on top of each other, or by providing an explicit mixer and LO for each required down-conversion, or a combination of the two. In this approach, all of the transmit energy is recovered but the S/N ratio achieved is inferior to the S/N ratio that would be obtained if the sub-bands were combined coherently.

Referring to Figure 9, another option is to coherently combine repeated OFDM symbols following the FFT. This coherent combining is performed in block 960. In this approach, maximum ratio combining of sub-bands may be used, in which each sub-band is multiplied by the complex conjugate of an estimated tap weight corresponding to the sub-band prior to additive combining. The wideband receiver must be capable of a baseband sample rate of two or three times the sample rate for a single sub-band (e.g., two or three times 528MHz). The corresponding FFT size is two or three times the size for single sub-band (e.g., 256 points or 384 points). In general, as indicated in Figure 9:

1. The bandwidth of the low-pass filters 211, 221 is N times the bandwidth required for a single sub-band.

2. The sample rate of the A/D converters 213, 223 is N times the sample rate required for a single sub-band.

3. The size of the FFT is N times that required for a single sub-band.

When all three sub-bands are used, the arrangement of Figure 9 effectively triples the spreading gain, i.e., coherent combining of several diverse versions of the signal, each of which is subject to uncorrelated noise, such that the SNR is improved by the same ratio (the spreading gain) as the number of copies of the signal combined. However, this improvement comes at the cost of substantial greater complexity, particular insofar as the size of the FFT is concerned.

In order to reduce this complexity, a combination of time and frequency spreading may be used. Referring to Figure 10, including Figure 10a, Figure 10b and Figure 10c, time-frequency spreading is illustrated. Figure 10a shows no spreading. A single sub-band is used at a time, and each OFDM symbol transmitted is different. In Figure 10b, 2x

spreading is used. The same OFDM symbols are transmitted within two different sub-bands at the same time. Within each sub-band, a particular OFDM symbol is transmitted twice consecutively. In Figure 10c, 3x spreading is used. The same OFDM symbols are transmitted within three different sub-bands at the same time. Within each sub-band, a particular OFDM symbol is transmitted three times consecutively. Note that the number of times a particular OFDM symbol is transmitted consecutively is the same as the number of sub-bands used at a time. This type of spreading may therefore be referred to as square time-frequency spreading.

Referring to Figure 11, examples of modified spreading schemes are shown consistent with the existing MB-OFDM proposal. For data rates from 53.3Mb/s to 200Mb/s, the existing MB-OFDM proposal provides for a time spreading factor (TFS) of 2. For these data rates, square time-frequency spreading may be achieved by introducing a corresponding frequency spreading factor of 2. For data rates of 53.3Mb/s and 106.7Mb/s, a frequency spreading factor of 3 is also made possible by increasing the TSF from 2 to 3, at the same time changing the coding rate from 1/3 to ½. The net effect of these changes is to maintain the same data rate.

Using square time-frequency spreading, it is possible to continuously occupy two or three sub-bands without increasing signal processing requirements. Referring to Figure 12, a block diagram is shown of a portion of a receiver for receiving a signal using NxN time-frequency spreading. Complex I,Q samples are buffered in an N-stage buffer 1210. The N-stage buffer stores the equivalent of N consecutive identical OFDM symbols for all of the sub-bands. A full overlap-add operation is then performed (1221), combining the N consecutive OFDM symbols into a single OFDM symbol. Adding is sufficient, since numeric scaling of the signal does not alter the information content, especially since the modulation employed is QPSK and only sensitive to phase values. Thus far, as in the case of Figure 9, the size of the required FFT is N times that required under the existing MB-OFDM proposal. At this point, in block 1223, decimation in frequency (a known signal processing technique) is used to form the data into N groups 1230, each group being of a size such that the required FFT is the same as required under the existing proposal. A sequencer 1241 is then used to allow the identical FFT hardware 1243 to perform the N (1x) FFTs in time-sequenced fashion. New inputs to the sequencer become available every N OFDM symbol periods. The sequencer outputs data for one 1x FFT every OFDM symbol period.

It will be appreciated by those of ordinary skill in the art that the present invention may be embodied in other specific forms without departing from the spirit or essential character thereof. The present description is therefore considered in all respects to be illustrative and not restrictive. The scope of the invention is indicated by the appended claims and not the foregoing description, and all changes which come within the meaning and scope of equivalents thereof are intended to be embraced therein.